

Electrical Bioimpedance Based Monitoring of Cardiac and Respiratory Activity: Positioning of Capacitive Electrodes for Wearable Human Monitoring Device

Margus Metshein, Toomas Parve

Th. J. Seebeck Dept. of Electronics, Tallinn University of Technology, Tallinn, Estonia

Correspondence: Margus Metshein, Th. J. Seebeck Dept. of Electronics, Tallinn University of Technology, Ehitajate tee 5, 19086, Tallinn, Estonia. E-mail: mmetshein@elin.ttu.ee, phone +3726202160, fax +3726202151

Abstract. In this paper, some observations concerning the capacitive measurements of respiratory and cardiac activity of human by using a wearable electrode shirt, are discussed. Electrode shirt is described and the results of the measurements are presented together with the charts of the signals. The related aspects, originating from the observations, concerning the measurement results and the design of electrode shirt, have been characterized. Additionally, the idea and the first prototype of an electronic device for capacitive monitoring of the rate of breathing and pulse of a human by the means of electrical bioimpedance is presented. An initial characterization of the prototype of the device is made through the comparison with the computer model. The initial results of the experimental measurements with the relevant discussion are provided. The conclusions are made related to the electrode positions, prototype of an electronic measurement device and the availability of breathing and heart rate.

Keywords: Capacitive Electrode, Electrical Bioimpedance, Electronic Measurement, Heart Rate, Respiratory Rate

1. Introduction

Monitoring of vital signs of human has become a key topic in personal healthcare. The reason is the widespread usage of smartphones induced by the development of the technology, the growth of the interest to the personal health etc. Following of breathing and heart rate (HR) and thus, of the gathered data, can be used to assess the overall health condition of human body. The totally new outputs unclosed for the medical doctors to follow the health of the patients from distance, for football coaches to follow the status of the players on the ground etc.

Electrical bioimpedance (EBI) is a tool that proposes a possibility of monitoring the vital processes of human. EBI is used to describe the response of the living organism to an externally applied electric current or voltage [Grimnes and Martinsen, 2008]. The fact that biological processes make the EBI variable in time makes it possible to follow the changes in organs and tissues by measuring the EBI [Bera, 2014].

Human body can be modeled by an electrical circuit that includes discrete components, resistors and capacitors. This approach, originated from the structure of a single cell and its surrounding space, where R_1 represents the extracellular liquid and R_2 and C_1 represent the intracellular liquid and the membrane of the cell allows to present dependency on the frequency of the electrical current (Fig. 1). Here the current with lower frequency flows mainly through R_1 , while at the same time currents with higher frequency find the way also through R_2 and C_1 [Grimnes and Martinsen, 2008].

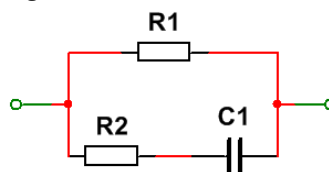


Figure 1. Basic electrical equivalent circuit of biological objects.

The variation of the EBI in time of a biological object can be presented as a serial connection of two impedances: constant impedance Z_{Con} and variable impedance Z_{Var} (Fig. 2). Z_{Con} represents the biological matter in the organism that does not depend on the change of the volume of blood and air: muscle, fat and bone. Z_{Var} depends on the changes in the volume of blood in circulatory system and air in respiratory system [Luna-Lozano et al., 2014].

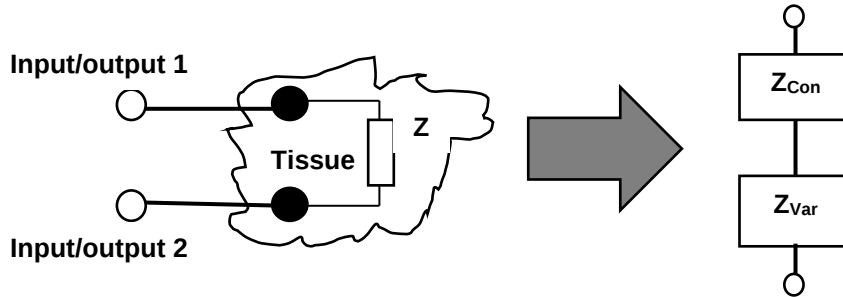


Figure 2. Equivalent representation of biological tissue through constant impedance Z_{Con} and the variable impedance Z_{Var} .

The variation in the volume of lungs during the in- and exhalation causes the impedance of trunk to change in accordance with the breathing. The same effect can be seen in the case of cardiac activity. Higher conductivity of the blood in the environment of relatively less conductive tissues open the possibility to monitor the periodic changes. These changes can be caused by the variation of the diameter of the blood vessels because of the pulsating blood or the variation of the volume of heart.

The usage of EBI for monitoring the vital signs is a subject of number of papers [Beckmann et al., 2007; Sahakian et al., 1985; Brown et al., 1994, etc.]. The main topics of this research had been the selection of the suitable positions for the electrodes on the trunk for monitoring the respiratory activity [Beckmann et al., 2007], the influence and the reduction of the effect of motions in the case of impedance pneumography [Sahakian et al., 1985], the study of changes of impedance of the body, caused by breathing and HR [Brown et al., 1994] etc., i.e. the aspects of the measurements of EBI.

The ideas of measuring EBI for determining breathing and HR are formed as wearable measurement devices and described by many research groups: the monitoring of the changing capacitance of the human trunk during the in- and exhalation [Luis et al., 2014]; the determination of the shift of wavelength in utilization of optics to monitor breathing [Xu et al., 2008]; the usage of inductive coil sensors for the monitoring of heart rate (HR) [Koo et al., 2014] etc. The EBI is among the popular technologies: a wearable wirelessly connected prototype of a device to monitor the condition on the tissues [Lee et al., 2013]; the measurement of the HR from forearm [Luna-Lozano et al., 2014] etc.

Nevertheless, there is no readymade device available that is able to detect the cardiac and respiratory activity of human by using large plate surface electrodes in capacitive connection. The problems, discussed in current paper, are related to some important aspects which appear during such measurements – the influence of motions, the small interval of change of real part of impedance, caused by cardiac activity etc.

For the experiments, an electrode shirt (ES), containing 15 different electrode placement configurations (EPC), was prepared. A number of measuring experiments were carried out and the best ones were selected. The results of the measurements and an exhaustive discussion of some observations are introduced. Additionally, an idea of an electronic wearable measurement device was proposed, a first prototype of a device was prepared and characterized. Initial measurements were done to verify the ability of the device to access the useful data of breathing and HR.

2. Devices and Properties

As a measuring device, HF2IS impedance spectroscopy of Zurich Instruments with HF2TA trans-impedance amplifier was used in the experiments. The specification of these devices defines the frequency range up to 50 MHz using either two- or four-electrode measurements.

Single types of electrodes were used in experiments: large wet plate surface electrodes of type 22 4773 Electrosurgical Grounding Plates by Niko Medical Products. The contact surface of the electrode was of dimensions 80 mm x 170 mm, made of aluminum foil and covered with contact gel [Metshein, 2015].

The measurements of the prototype of the custom made measurement device were done by using the Infiniium 9000 series oscilloscope DSO9204H of Agilent. This device offers the bandwidth up to 2 GHz and maximum sample rate of 10 GSa/s.

3. Methods

The custom made ES was used in the experiments (Fig. 3). ES was a cotton shirt of thickness of 0.5 mm, covered by large wet surface plate electrodes according to chosen concept. The locations of the electrodes were selected in a way that the whole back, shoulders and the sides of the trunk were covered with the goal of accessing the data of breathing and HR.



Figure 3. Photo of the electrode shirt.

Altogether 18 pieces of indexed electrodes were used in the ES (Fig. 4). The indexing was needed to combine the electrodes into different EPC's and make the later documenting and analysis easier [Metshein, 2015].

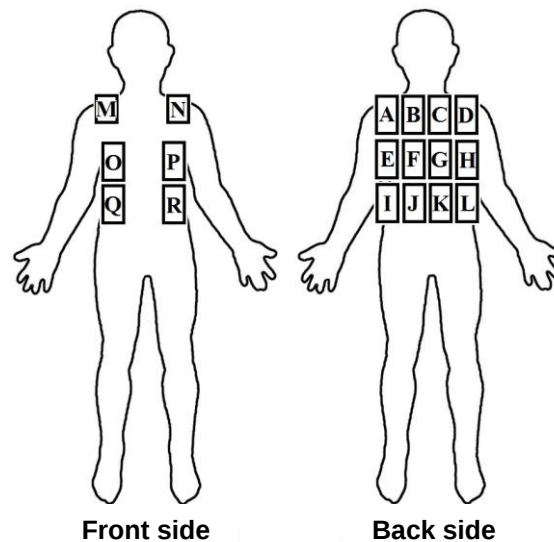


Figure 4. Position of the electrodes on the electrode shirt [Metshein, 2015].

Fifteen different EPC's were experimented. In cases where there were more electrode positions used for one operation (measuring or exciting), electrodes were connected together with wires to achieve the required EPC's [Metshein, 2015].

All the measurements were done by using four-electrode method at the frequency of 10 MHz and excitation voltage with the amplitude of 500 mV.

The choice of the relatively high excitation frequency is explained by the properties of the ES – as the shirt was a commercial cotton shirt of regular fit that is not in reliable nearness of the skin. The peculiarities of capacitive connection were expected to appear. To artificially increase the minimum distance between the electrodes and the skin, another cotton shirt of thickness of 0.5 mm was placed under the ES [Metshein, 2015].

The experiments, were done only with a single individual. As the locations of the parts of respiratory and circulatory systems in human body are, with small differences quite the same, this is presented to be acceptable [Metshein, 2015].

4. Measurement Results

A number of measurement experiments were carried out by using different EPC's. As the outcome of the measurements, the real part (ReZ) of total impedance (modulus $|Z|$) was used as an instantaneous value without calculations. This was chosen because of the property of biological objects to have mostly active character [Metshein, 2014].

The object was dressed into the ES and asked to fulfill certain program of movements.

To evaluate the EPC's, two parameters were retain [Metshein, 2015]:

1. the ratio of change of ReZ, caused by the respiratory and cardiac activity of total ReZ;
2. the ratio of change of ReZ, caused by the respiratory and cardiac activity of the interval of ReZ, caused by motions.

The results of the measurements can be seen in Fig. 5-6 and Table 1-2. Table 1 and 2 show the results of breathing and HR separately: the ratio of change of ReZ, caused by breathing and HR of total ReZ; the ratio of change of ReZ, caused by breathing and HR to interval of ReZ, caused by motions [Metshein, 2015]. Fig. 5-6 are visually demonstrating the comparison between the best and worst results of the results of the measurements of breathing and HR.

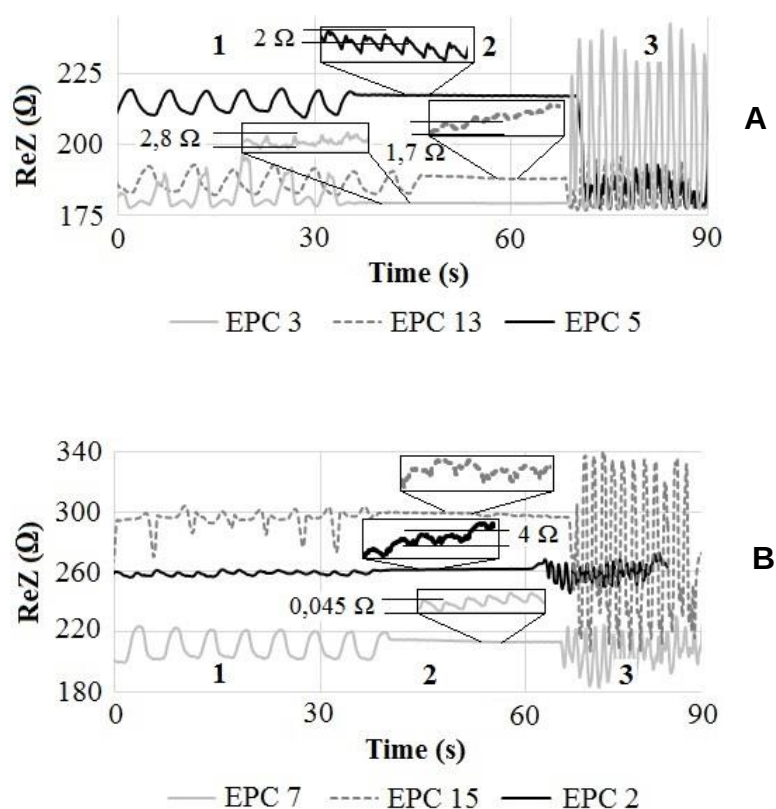


Figure 5. Comparison of the best (A) and the worst (B) results of measurements of HR of parameter 2 in the cases of (1) deep breathing, (2) standing still while holding the breath and (3) imitating the swimming while holding the breath.

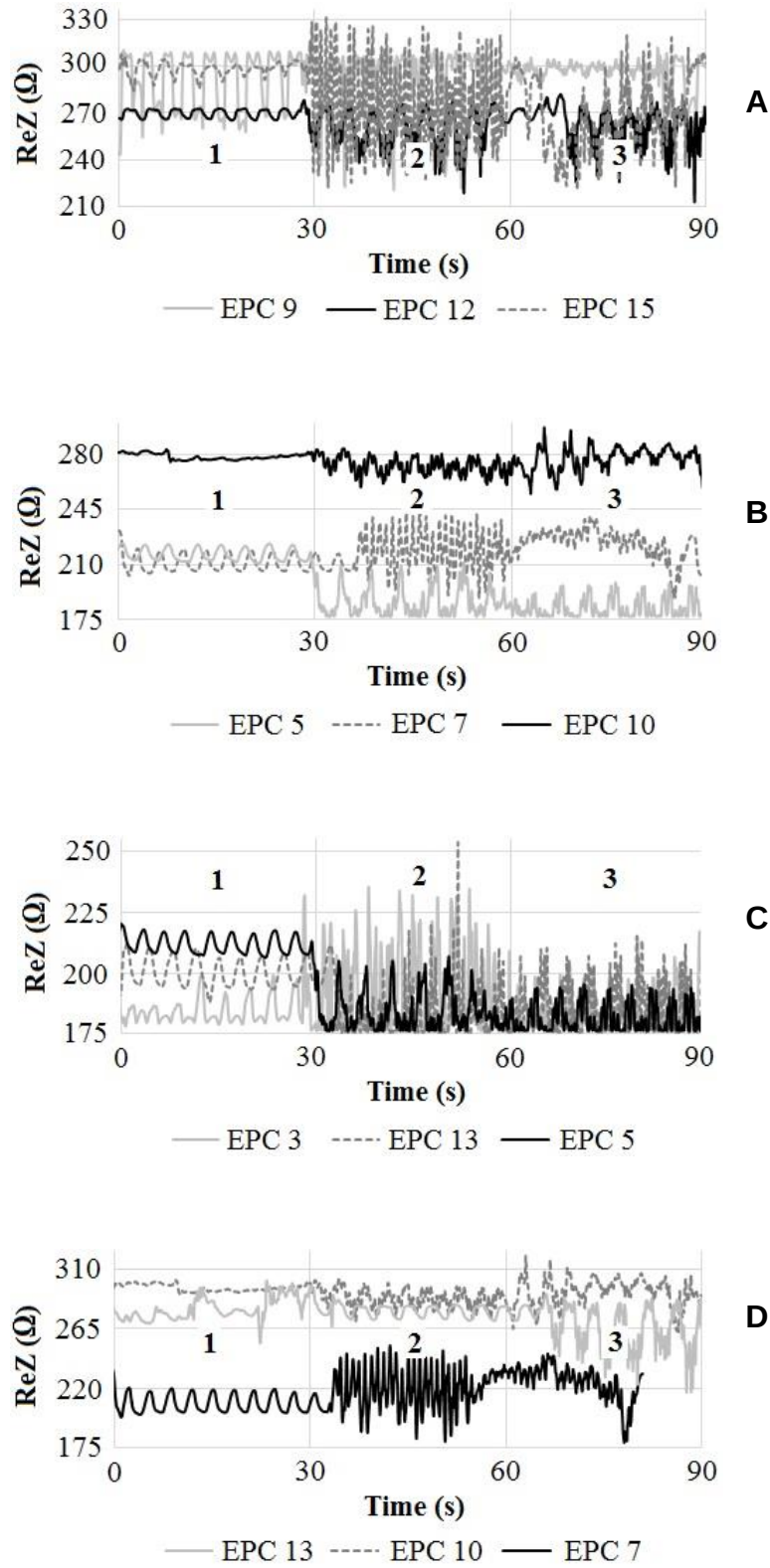


Figure 6. Comparison of the best (A) and the worst (B) results of measurements of breathing of parameter 1 and the best (C) and the worst (D) results of measurements of parameter 2 in the cases of (1) deep breathing, (2) squatting with deep breathing and (3) splurging the hands while holding the breath.

Table 1. The results of the measurements of breathing with the electrode shirt [Metshein, 2015].

<i>EPC</i> <i>nr.</i>	<i>EPC</i>	<i>Ratio of breathing</i> <i>from total ReZ</i> <i>(%)</i>	<i>Ratio of breathing</i> <i>from interval of ReZ</i> <i>of motions (%)</i>
1	Exc. MN and IJKL, meas. ABCD and EFGH	44 - 83	34 - 71
2	Exc. AEIN and DHLM, meas. BFJ and CGK	54 - 90	34 - 50
3	Exc. MN and OP, meas. ABCD and EFGH	66 - 90	80 - 90
4	Exc. O and P, meas. ABEFIJN and CDGHKLM	33 - 62	56 - 87
5	Exc. NP and MO, meas. ABEFIJ and CDGHKL	21 - 62	77 - 83
6	Exc. AB and KL, meas. CD and IJ	40 - 60	34 - 48
7	Exc. NA and MD, meas. B and C	32 - 42	7 - 10
8	Exc. NPR and MOQ, meas. EFIJ and GHKL	64 - 90	44 - 90
9	Exc. EFIJ and GHKL, meas. O and P	80 - 90	43 - 70
10	Exc. NPR and MOQ, meas. ABEFIJ and CDGHKL	21 - 27	21 - 30
11	Exc. NPR and MOQ, meas. FJ and GK	38 - 90	44 - 90
12	Exc. PR and OQ, meas. ABCD and IJKL	74 - 90	24 - 30
13	Exc. MN and OPQR, meas. ABCD and IJKL	28 - 90	80 - 90
14	Exc. MN and OPQR, meas. EFGH and IJKL	47 - 90	50 - 90
15	Exc. BFJ and CGK, meas. NPR and MOQ	73 - 90	51 - 59

Table 2. The results of the measurements of HR with the electrode shirt [Metshein, 2015].

<i>EPC</i> <i>nr.</i>	<i>EPC</i>	<i>Ratio of breathing</i> <i>from total ReZ</i> <i>(%)</i>	<i>Ratio of breathing</i> <i>from interval of ReZ</i> <i>of motions (%)</i>
1	Exc. MN and IJKL, meas. ABCD and EFGH	0,3 – 0,7	0,4 – 0,7
2	Exc. AEIN and DHLM, meas. BFJ and CGK	0,6 – 1,0	0,1 – 0,2
3	Exc. MN and OP, meas. ABCD and EFGH	1,6 – 5,3	1 – 4
4	Exc. O and P, meas. ABEFIJN and CDGHKLM	0,5 – 2,0	0,9 – 1,3
5	Exc. NP and MO, meas. ABEFIJ and CDGHKL	0,7 – 3,0	1,5 – 8,3
6	Exc. AB and KL, meas. CD and IJ	0,4 – 0,8	0,6 – 1,0
7	Exc. NA and MD, meas. B and C	0,4 – 0,8	0 – 0,1
8	Exc. NPR and MOQ, meas. EFIJ and GHKL	1,4 – 3,6	0,7 – 1,8
9	Exc. EFIJ and GHKL, meas. O and P	1,5 – 3,6	0,4 – 0,9
10	Exc. NPR and MOQ, meas. ABEFIJ and CDGHKL	0,5 – 1,2	0,6 – 1,4
11	Exc. NPR and MOQ, meas. FJ and GK	0,2 – 0,7	0,4 – 0,7
12	Exc. PR and OQ, meas. ABCD and IJKL	1,2 – 2,2	0,2 – 0,3
13	Exc. MN and OPQR, meas. ABCD and IJKL	1,2 – 2,3	2,0 – 8,3
14	Exc. MN and OPQR, meas. EFGH and IJKL	1,3 – 2,2	0,9 – 1,0
15	Exc. BFJ and CGK, meas. NPR and MOQ	0,7 – 0,8	0,2 – 0,3

In current paper, the results are presented in percentages, separately for respiratory and cardiac activity, showing the outcomes of repeated measurements for each EPC. The reason is the high dependability of the measurement results to motions and the variation in wide range.

The best and worst results of breathing concerning parameter 1 are EPC's 9 and 10 respectively. The best and worst results of the same parameter of HR are EPC's 3 and 1. The best and worst results of breathing concerning parameter 2 are EPC's 3 and 7. The best and worst results of the same parameter of HR are EPC's 13 and 7. During the experiments, the sets of data were gathered and saved for later generation of the illustrative charts. The charts are composed of 3 best and 3 worst results and can be divided in two groups: respiratory activity and cardiac activity.

Breathing is visually available in majority of the cases of charts. Nevertheless, the amplitude of HR is low enough to disappear in the cases of representing it in the same scale with the affection of the movements (Fig. 5). For this reason the magnification of the shape of the signal of HR is shown in bordered box nearby. This is the reason, why only two charts, representing the three best and three worst results of parameter 2, are shown in current paper.

5. Realization and the Characterization of the First Prototype of a Custom Cade Electronic Measurement Device

In this chapter, the idea and a prototype of a custom made electronic measurement device for monitoring breathing and HR by the means of EBI by using capacitive connection to the object, is presented. The initial characterization is done on the ground of the preliminary measurements and compared to the computer simulation. The basic principle and the experimental setup are described together with the ongoing developments and plans for the future improvements. The goal is to study the possibility of monitoring the breathing and HR by using the ES.

5.1. Basic Principle and the Realization of the Electronic Measurement Device

The idea of the device includes the excitation of the object by a square wave signal and measuring of the real part ($\text{Re}Z$) of the total impedance (modulus $|Z|$) by using two-electrode configuration. First, the signal is amplified with an inverting amplifier with the gain of 10, synchronously switched by analog switch and finally low- and high pass filtered (Fig. 7). The frequency band, formed by low and high pass filters was chosen to be 0,1 – 10 Hz and can be calculated by using Eq. 1.

$$F_{\text{Cutoff}} = \frac{1}{2\pi RC} \quad (1)$$

where

F_{Cutoff} = cut-off frequency

R = resistance

C = capacitance.

The output of the device is dc voltage, which value is expected to increase or decrease because of the in- and exhalation and the changing amount of blood in vessels. The calculation of the value of $\text{Re}Z$ is planned to be done by proceeding stages of the device.

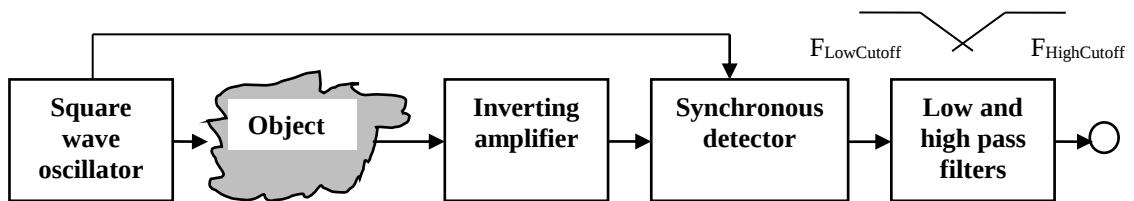


Figure 7. Block diagram of the custom made electronic measurement device.

The device was realized with discrete electronic components and prototyping printed circuit board (PCB). The square wave generator was based on logic NAND gates of type 74HCT00D and the output was set to 6 MHz – the maximum frequency where the generated square wave was tolerably symmetrical. The op-amps were of type LT6221CS8 by Linear Technology, offering the bandwidth of 60 MHz. The same parameter of the analog switch was 100 MHz, offered by type TS5A3159 of Texas Instruments.

5.2. Characterization of the Device

For setting the configuration of the circuit and evaluating the readymade prototype, a computer model in modelling environment Multisim 13.0 was composed. The virtual op-amps with adjustable parameters were used and the tolerances of passive components were chosen to be the same as in readymade prototype.

In the computer model, human trunk was represented by a single resistor and CMOS transistor of type VN10LF by Diodes Inc. The ratio of voltage divider was set to 10:1, setting the invariable value of the total impedance.

The amount of the change of ReZ was set by the variable resistance of the channel of MOSFET, driven by the function generator with a sinus signal of frequency of 20 KHz with amplitude of 0.1V and offset of 2.25V. These values were set by observing the modulation on top of the carrier signal to be visually maximally symmetrical.

The output signal of the computer model showed the availability of the change of the resistance of the MOSFET channel (Fig. 8), constituting approximately 6% of the peak of the measured voltage.

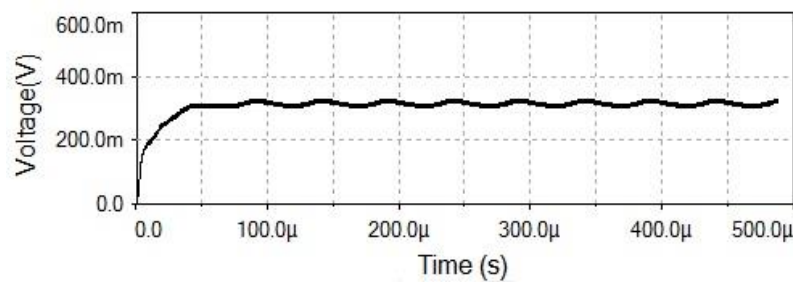


Figure 8. The shape of the signal at the output of the computer model.

5.3. The Setup and Initial Results of Experimental Measurements with the Electrode Shirt

For testing the custom made electronic measurement device, the previously described ES was used. Nevertheless, two-electrode configuration setup by using a different and previously not characterized EPC was utilized. The chosen placement of electrodes cradles the idea of vertically covering the area, where the lungs, heart and large blood vessels are located (Fig. 9). The object was dressed into the shirt, asked to stand still and breathe deeply.

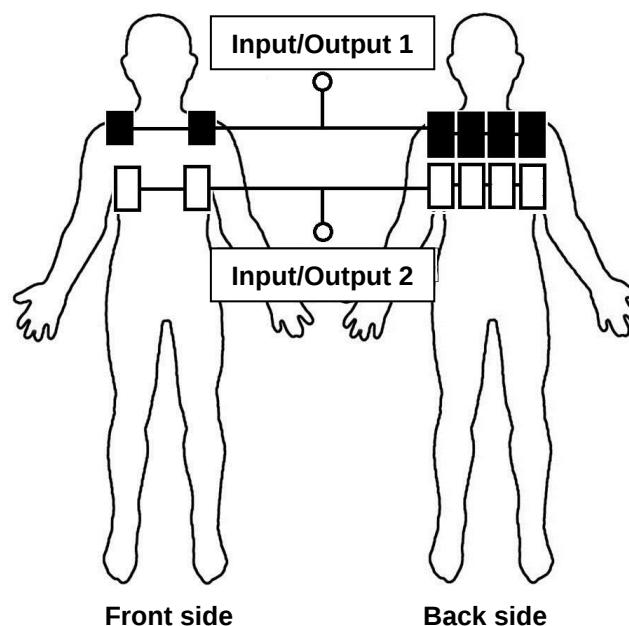


Figure 9. The setup of the measurement by using the electrode shirt.

The result is shown as voltages in time scale, representing the change of the impedance of the trunk (Fig. 10). From the achieved result, the availability of breathing can be seen (three recognizable

breathing cycles in Fig. 10). Nevertheless, HR cannot be recognized by the eye – the reason is assumed to be the small change of ReZ, caused by the pulsating blood, when compared to the additive distortions – presuming the utilization of special algorithms.

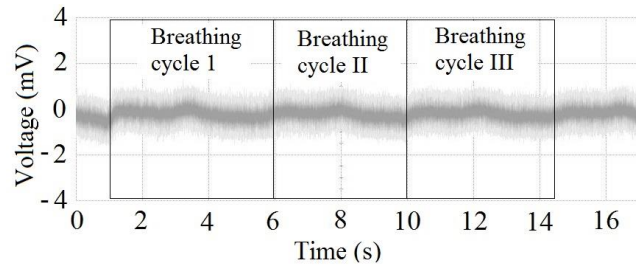


Figure 10. The measured signal at the output of the custom made electronic measurement device in the case of measuring breathing and HR of a real living subject.

The measurement result is containing high frequency (HF) noise of 100 MHz (seen as blurred line of the signal in Fig. 10). This is assumed to be caused by the external noise sources, which are affecting the measurement setup by the long leads, the discrete electronic components in the design of the prototype etc. This effect was present despite a first-order low-pass filter with cut-off frequency of 530 Hz that was placed at the input of oscilloscope for the measurement experiment.

The amplitude of the measured voltage, caused by in- and exhalation, stays in the range of 0.5 mV. At the same time, the amplitude of the noise reaches up to 1 mV. The frequency of breathing can be calculated according

$$F = \frac{1}{T} \quad (2)$$

where

F = frequency of breathing (Hz)

T = duration of breathing cycle (s).

According to the recognizable three cycles in Fig. 10, the frequency of breathing of the object is about 0.25 Hz, constituting about 15 breaths per minute.

6. Discussion Related to Some Aspects

Subsequently, some relevant aspects and observations are discussed in the frames of the usability of experimented EPC's in a lineup of wearable measurement garment. The thorough analyze of the represented results is available in [Metshein, 2015].

The information in the table can be misleading in some aspects – mainly in the numerical and visual representation of the results. Namely, according to Table 1, an EPC may belong, concerning a chosen parameter, among the worst ones, but shows in visual checking a very distinctive representation of result. As a sample, EPC 7 can be named, showing the visually clear cycles of breathing in the case of deep breathing but obscuring totally the possibility of identifying the same process in the case of squatting with deep breathing (Fig 6, chart D).

The reasons for this phenomenon may be different and depend on the choice of the placement of the electrodes. One of these can be that, in EPC 7, the configuration of exciting at both of the shoulders and measuring at the center of the back, is used. The assumption is: during the squatting, the object held his hands outstretched, while during the standing, the hands were hanging vertically of the trunk. The position of the ES might have dislocated or continuously changing its position relative to the skin surface and interfering the results by varying the value of capacitive element of the connection with the body.

Second important observation hereby is the measurement result of breathing in the cases of splurging the hands while holding the breath (Fig. 6, charts A and B, part 3). During the experiments, it was seen that splurging the hands can be used to imitate breathing while holding the breath during the measurement of impedance. By analyzing the charts, this can be observed in the case of EPC 5 (Fig. 6, charts B and C), splurging of the hands clearly resembles the shape of the signal of deep breathing. At the same time, in the case of EPC 9 (Fig. 6, chart A), the shape of the signal, caused by splurging the hands is visually clearly distinguishable from deep breathing.

One of the reasons for the described property is assumed to be the same as already presented in this chapter – the displacement of the ES is causing the measured impedance to vary because of the periodical

movement of the hands. Nevertheless, the reason might also be anatomical – splurging the hands stretches the lungs and increases its volume. The outcome is assumed be the same that can be seen in presented charts: the change of the measured value of ReZ of the trunk that, in visual study, seems to represent breathing. A research of this phenomena is described in [Khambete et al., 2000], where a specific six-electrode configuration is utilized to suppress the body related movements.

When designing a wearable measurement device in the form of garment, more than one EPC for following breathing or HR is suggested to be utilized. If a person, wearing the garment, is not standing still but is moving, the clothing is most probably dislocated. In some body positions, some EPC's may give better access to the data of respiratory and HR and in other positions, the other EPC's may be usable to achieve the strongest signal.

Another important aspect binds to the results of the measurements of HR. The difference between the maximum and minimum values of the peaks of waveforms, caused by the respiratory and cardiac activity, are large and not visually available in the same scale – shown already in [Metshein, 2015]. The latter fact can be seen in Fig. 7 (charts A and B), where the comparison of cardiac activity with the signal of breathing and affection of motions is visible. The analyze of Table 2 concerning parameter 1 of HR shows that it is reasonable to assume that the cardiac activity is available on top of the waveform of breathing and also on top of the waveform of motions. By taking a close extract of the signal, this corresponds to the truth (Fig. 7).

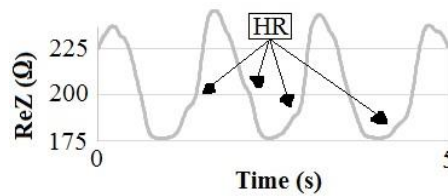


Figure 11. A snapshot of the result of the measurements by using the EPC 3 with showing the visible peaks of HR in the case of imitating the swimming while holding the breath.

The latter observation gives a promising base for the hope that, by the help of signal processing, HR can be detected. Nevertheless, it can be assumed that during the intensive moving of the body, the motion artefacts are still interfering the signal of HR. The suggestion is that the extracting should not be implied to be done continuously – the algorithm can be set to follow the shape of the signal and detect HR periodically. The idea is to recognize the starts of the potentially fatally interfered periods of time of the signal and tell the machine to hold the last value.

7. Conclusions

A number of aspects were presented, related to the results of the experiments and the described observations. The capacitive measurements of EBI of the trunk of a human by using a custom made ES demonstrated the availability of breathing and HR. The visual availability of beneficiary signal may differ from the numerical result – the reason is assumed to be the displacement of the shirt during the movements. The splurging of the hands while holding the breath may generate a waveform that resembles breathing. The signal of HR is available even in the case of movements of the body – it is carried by the larger waveform and is suggested to be extracted by using special algorithms.

The preliminary results of the capacitive measurements by using the first prototype of the custom made electronic measurement device show the availability of breathing. Nevertheless, the data of HR is not visually available because of the concurrent HF noise. This HF noise is expected to be further suppressed after the preparation of subsequent prototype of the device.

The novelty of the current paper can be found from the usage of large wet surface plate electrodes, attached on a cotton shirt as capacitive measurement devices, for monitoring EBI. Several EPC's were experimented to evaluate the availability of breathing and HR and a number of related aspects were discussed. A first prototype of a custom made electronic measurement device was prepared and experimented to measure the breathing and HR by using the capacitive connection to the subject.

The plans for the future include the preparation of the next version of the ES, where the electrodes are placed onto the best known placements, presented also in this paper. The discussed observations and ideas will be keep in mind together with the ideas of varying the size and type of the electrodes. The full characterization of the prototype of the measurement device and the calculations of the output signal will be done together with switching to battery based power supply. The long-term and already ongoing task is to develop an electronic device, installed into the garment, for monitoring the impedance of the trunk to determine the breathing and HR.

Acknowledgements

This research was supported by European Union through the European Regional Development Fund in frames of the research center CEBE and competence center ELIKO.

References

- Beckmann L, van Riesen D, Leonhardt S. Optimal electrode placement and frequency range selection for the detection of lung water using bioimpedance spectroscopy. In proceedings of the 29th Annual International Conference of the IEEE EMBS, 2007, 2685-2688.
- Bera TK. Bioelectrical impedance methods for noninvasive health monitoring: A review. *Journal of Medical Engineering*. 2014; 1-28, 2014.
- Brown BH, Barber DC, Morice AH, Lethard AD. Cardiac and respiratory related electrical impedance changes in the human thorax. *IEEE Transactions on Biomedical Engineering* 41(8): 729-734, 1994.
- Grimnes S, Martinsen ØG. Bioimpedance & Bioelectricity Basics. Academic Press, London, 2008.
- Khambete ND, Brown BH, Smallwood RH. Movement artefact rejection in impedance pneumography using six strategically placed electrodes. *Physiological Measurement* 21(1): 79-88, 2000.
- Koo HR, Lee Y-J, Gi S, Khang S, Lee JH, Lee J-H, Lim M-G, Park H-J, Lee J-W. The effect of textile-based inductive coil sensor positions for heart rate monitoring. *Journal of Medical Systems*, 38(2):2, 2014.
- Lee S, Polito S, Agell C, Mitra S, Yazicioglu RF, Riistama J. A low-power and compact-sized wearable bio-impedance monitor with wireless connectivity. *Journal of Physics Conference Series*. 434(1): 2013-, 2013.
- Luis JA, Roa Romero LM, Gómez-Galán JA, Hernández DN, Estudillo-Valderrama MÁ, Barbarov-Rostán G, Rubia-Marcos C. Design and implementation of a smart sensor for respiratory rate monitoring. *Sensors*, 14(2): 3019-3032, 2014.
- Luna-Lozano PS, García-Zetina OA, Pérez-López JA, Alvarado-Serrano C. Portable device for heart rate monitoring based on impedance pletysmography. In proceedings of the 11th International Conference on Electrical Engineering, Computing Science and Automatic Control (CCE), 2014, 1-4.
- Metshein M. Alternatives of measurement of electrical bioimpedance of the body with the aim to determine the cardiac and respiratory activity. In Proceedings of the 14th Biennial Baltic Electronics Conference (BEC2014), 2014, 197-200.
- Metshein M. A device for measuring the electrical bioimpedance with variety of electrode placements for monitoring the breathing and heart rate,” In Proceedings of the 26th Irish Signals and Systems Conference (ISSC), 2015, 1-4.
- Sahakian AV, Tompkins WJ, Webster JG. Electrode motion artifacts in electrical impedance pneumography. *IEEE Transactions on Biomedical Engineering*, 32(6): 448-451, 1985.
- Xu X, Zhang C, Hou KM, Ding H, Diao X. A new wireless fiber optic sensor for monitoring breath motion. In proceedings of the New Technologies, Mobility and Security, 2008. NTMS '08, 2008, 1-5.